Final Report for Small Thermoacoustic Refrigerator

Submitted by:
Professor Ralph Muehleisen
Civil, Environmental, and Architectural Engineering
University of Colorado
Campus Box 428
Boulder, CO 80309
ralph.muehleisen@colorado.edu
http://civil.colorado.edu/~muehleis

Introduction:

This is the final report for the project entitled Small Thermoacoustic Refrigerator (SMATAR) supported by ONR grant N00014-99-1-0217 from Feb. 1, 1999 to Jan. 31, 2000. The purpose of the project was to develop a small thermoacoustic refrigerator. The refrigerator was fit into a 4-6 in^3 package, cool over a 30 °C temperature span and provide 2W of cooling with one atmosphere air as the working fluid and 10 W of cooling with one atmosphere helium as the working fluid.

At the end of the granting period the refrigerator design fit in a 6 in^3 package, but was not providing the required cooling capacity. At the end of November 1999 the system was providing 0.5W of cooling over a 4 °C temperature span using air at atmospheric pressure span but the chosen driver element was unable to provide the required acoustic output. As a result the system is being redesigned around a different acoustic driver. Work on the project will continue with the renewal of the grant.

Project Goals

The main goal of this research project was to develop a small thermoacoustic refrigerator capable of producing 10W of cooling over a 30 °C temperature span in a 4 to 6 in^3 form factor with a 10% driver ratio. In order to meet these goals the refrigerator would use helium at one atmosphere as the working fluid. The thermoacoustic stack would be a rolled mylar and the heat exchangers would be copper screen mated to copper tubing. The transducer would be an inexpensive piezo tweeter element. Because of the size and materials used the cost would be quite inexpensive (we would expect the units to cost well under $10 each in production). To achieve larger cooling powers multiple units would be used in parallel.

As modeled in DELTAE, the system is predicted to achieve 15 W of cooling over the 30 °C temperature span using one atmosphere helium as the working fluid and a 15% drive ratio. Given the accuracy of DELTAE and the fact that we had to use approximate

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Muehleisen, Ralph T.

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CIVIL ENVIRONMENTAL AND ARCHITECTURAL ENGINEERING
UNIVERSITY OF COLORADO
CAMPUS BOX 428
BOULDER CO 80309-0428

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
OFFICE OF NAVAL RESEARCH
0NR 331
800 NORTH QUINCY STREET
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14. ABSTRACT
The purpose of the project was to a Small Thermoacoustic Refrigerator (SMATAR) capable of providing 10W of cooling using 2 bar helium or 2 W using 1 bar air over a 25 K temperature span in a 4 cubic inch package. The device was to use inexpensive transducers and stack and heat exchanger materials and be easy to manufacture. At the end of the grant period, a basic design was complete on paper but the prototype was not yet constructed. The prototype as constructed was capable of providing 0.5W of cooling over a 4 K temperature span using one bar air as a working fluid.

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models for the stack and heat exchangers we hoped to be able to achieve about 10 W of cooling.

Accomplishments

The initial development of SMATAR was delayed because the undergraduate lab assistants had to be brought up to speed on basic thermoacoustic theory in order to be able to help with the design and construction. Initial computer modeling was complete in June of 1999 and construction began soon thereafter.

Over the summer, the students and Prof. Muehleisen adjusted the design in order to ease manufacturing constraints. One of the goals of the simple design was to reduce manufacturing costs by utilizing as much "off the shelf" materials as possible. Because of those constraints, the rolled mylar stack was replaced with a nylon stacked-screen stack. The individual nylon screen mesh elements were easily punched from off the shelf nylon screen mesh. Following the suggestion of other ONR sponsored researchers, the mesh size was chosen to be twice the optimal spacing of the rolled mylar stack.

The copper mesh heat exchangers were easily punched from copper mesh screening. The heat exchanger mounts were initially machined from copper, but the machining was too slow so subsequent mounts were machined from aluminum. The copper screens were fastened to the aluminum mounts using thermally conductive adhesives obtained from the Omega corporation.

The refrigerator was constructed with thermocouples placed throughout the system. Thermocouples were placed at the center, inside mount edge and outside mount edge of the heat exchangers. The temperature difference on the inside and outside edge of the heat exchanger mounts was used to determine the heat flow through the heat exchanger. Thermocouples were also placed in the center and edge of the stack, midway between the two heat exchangers.

The initial transducer was a Motorola piezoelectric tweeter unit that was claimed to have a sensitivity of 100 dB at 1 W/1m in free space and an input power limit of 400 W electrical power. That unit should have been capable of linearly producing at least a 10% drive ratio ($p_{acoustic}/p_{mean}$) within the tube, but was not. At the end of October it was learned that the 100 dB rating was achieved with an exponential horn attached to the tweeter and without the horn the unit was only capable of providing 90 dB at 1W/1m.

At the end of October, tests of the unit showed a performance of 0.5 W of cooling over a 4 °C temperature span. These results were reported at the Fall ASA meeting by the undergraduate students. The unit was unable to provide better performance because the acoustic driver unit was limited to providing about a 1% drive ratio to the refrigerator.

Another drawback to the initial design was that although machining of individual parts was easy and inexpensive, modifications to the system such as adjusting resonator lengths and stack lengths were not easily made. Thus in the beginning of November the

system underwent a redesign to ease systematic variation of system components such as stack length and mesh size and resonator length. Over winter break, neither of the undergraduate students was able to spend much time working in the laboratory and thus no further tests were made before the end of the grant period. The work will continue in spring, summer and fall of 2000 as the grant has been renewed for another 11 months.

Despite the seemingly small progress made, there are some important findings to report for other researchers in the field.

1) Copper mesh screens can be used as effective heat exchangers in small thermoacoustic designs. Temperature measurements with 0.5 W of cooling showed a temperature variation of about 0.5 °C from the middle of the screen to the edge. This was a minimal design utilizing one layer of #12 mesh. When the power increases to 10 W one would expect a 10 °C deficit using the same heat exchanger design, but if one scaled up the screen mesh size to #10 and utilized two adjacent layers, the conductive area between the center of the mesh and the edge of the heat exchanger mount would increase four-fold which would drop the temperature deficit to a reasonable 2.5 °C.

2) Nylon mesh may be applicable to a stacked screen refrigerator. While the properties of nylon would not be appropriate at cryogenic temperatures, at room temperatures and small variations from room temperature, the high heat capacity and low thermal conductivity of nylon make it an excellent candidate for stacks in small engines. Nylon mesh screen is available in a variety of sizes and porosities and is quite inexpensive. Because we did not construct a helium device, the potential outgassing problems of nylon have not been investigated.

3) Undergraduate student researchers can be effective researchers when properly focused. However, compared to graduate students, undergraduate students will normally spend far fewer hours per week in the lab and will often have those hours broken into many small segments which can severely limit their productivity. The opportunity to play a major role in the development of SMATAR and the successful presentation of the limited results at a national conference was a significant event in the professional development of the undergraduate students.

Future Plans

With the renewal of the grant, development of SMATAR will continue. However, the main focus of the work will lie in other directions. In the modeling of SMATAR, the stack was assumed to be a parallel plate stack because a model for a stacked screen appropriate for a standing wave heat engine does not exist. We will use previous research in the acoustics of porous media and make measurements of stacked nylon screens to develop a useful and accurate model of a stacked screen in standing wave thermoacoustic engines. We will also investigate the choice and design of heat exchangers for small refrigerators and heat engines.

Appendix 1: Deltae Model

The following is an example of a deltae output from a typical design run. The beginning block defines the system to use 2 bar helium and a drive ratio of 10%. The hot heat exchanger (block 3) shows a heat flow of +13W and a temperature of 300K while the cold heat exchanger shows a heat flow of –14W and a temperature of 275K, showing a design cooling power of over 10W and a temperature span of 25 K.

```
TITLE     SMATAR with 2 bar helium and plastic tubing
!->sa13.out
!Created@17:15: 0  1-Jan-** with DeltaE Vers. 4.5b7 for the IBM/PC-Compatible
!--------------------------------- 0 ---------------------------------
 BEGIN      0
  2.0000E+05 a Mean P    Pa                4689.5     A Freq.  G( 0b)      P
  4689.5     b Freq.     Hz      G          291.68    B T-beg  G( 0c)      P
   291.68    c T-beg     K       G       5.9599E-04 C |U|@0  G( 0f)      P
  2.0000E+04 d |p|@0     Pa                 13.355    D HeatIn G( 3e)      P
     0.0000  e Ph(p)0    deg
  5.9599E-04 f |U|@0     m^3/s   G
     0.0000  g Ph(U)0    deg
 helium      Gas type
 ideal       Solid type
!--------------------------------- 1 ---------------------------------
 ENDCAP      Driver end                1
  6.4000E-04 a Area      m^2              2.0000E+04 A |p|        Pa
                                             0.0000  B Ph(p)      deg
                                          5.6791E-04 C |U|      m^3/s
                                             0.0000  D Ph(U)      deg
                                             5.6791  E Hdot       W
 sameas   0  Gas type                        5.6791  F Work       W
 mylar       Solid type                     -0.2808  G HeatIn     W
!--------------------------------- 2 ---------------------------------
 ISODUCT     Room temp duct            2
 sameas  1a  a Area      m^2              1.9861E+04 A |p|        Pa
  8.9000E-02 b Perim      m              -9.6658E-02 B Ph(p)      deg
  4.0000E-03 c Length     m               4.5640E-03 C |U|      m^3/s
                                            -83.098  D Ph(U)      deg
                                             5.5227  E Hdot       W
 sameas   0  Gas type                        5.5227  F Work       W
 mylar       Solid type                     -0.1564  G HeatIn     W
!--------------------------------- 3 ---------------------------------
 HXFRST      Room temp duct heat         3
 sameas  2a  a Area      m^2              1.9274E+04 A |p|        Pa
     0.4400  b GasA/A                       -0.1487  B Ph(p)      deg
  3.0000E-03 c Length     m               6.0861E-03 C |U|      m^3/s
  5.0000E-04 d y0         m                 -85.570  D Ph(U)      deg
    13.355   e HeatIn     W      G           18.878  E Hdot       W
   300.00    f Est-T      K     = 3H?        4.6822  F Work       W
 sameas   0  Gas type                        13.355  G Heat        W
 copper      Solid type                      300.00  H MetalT      K
!--------------------------------- 4 ---------------------------------
 STKSLAB     Stack                     4
 sameas  2a  a Area      m^2              1.9258E+04 A |p|        Pa
     0.8000  b GasA/A                       -0.1093  B Ph(p)      deg
  1.0000E-04 c Length     m               6.1644E-03 C |U|      m^3/s
  7.0000E-05 d y0         m                 -85.564  D Ph(U)      deg
  2.0000E-05 e Lplate     m                  18.878  E Hdot       W
                                             4.7037  F Work       W
                                             291.68  G T-beg       K
 sameas   0  Gas type                        288.19  H T-end       K
 mylar       Solid type                  2.1562E-02 I StkWrk      W
```

```
!--------------------------------- 5 ---------------------------------
 HXLAST     Cold temp duct heat         5
 sameas  2a  a Area      m^2              1.9020E+04 A |p|       Pa
 sameas  3b  b GasA/A                       -0.1146  B Ph(p)     deg
  1.0000E-03 c Length     m               6.6618E-03 C |U|     m^3/s
 sameas  3d  d y0         m                 -86.113  D Ph(U)     deg
     1.0000  e HeatIn     W      (t)         4.4212  E Hdot      W
   275.00    f Est-T      K    = 5H?         4.4212  F Work      W
 sameas  0  Gas type                        -14.457  G Heat      W
 copper     Solid type                       275.00  H MetalT    K
!--------------------------------- 6 ---------------------------------
 ISODUCT    Cold Duct                  6
 sameas  2a  a Area      m^2              1.9332E+04 A |p|       Pa
 sameas  2b  b Perim      m               -179.99    B Ph(p)     deg
     0.1000  c Length     m               2.6854E-05 C |U|     m^3/s
                                          -179.99    D Ph(U)     deg
                                             0.2596  E Hdot      W
 sameas  0  Gas type                         0.2596  F Work      W
 mylar      Solid type                      -4.1616  G HeatIn    W
!--------------------------------- 7 ---------------------------------
 ENDCAP     Second end                  7
 sameas  2a  a Area      m^2              1.9332E+04 A |p|       Pa
                                          -179.99    B Ph(p)     deg
                                          4.0619E-14 C |U|     m^3/s
                                          -111.78    D Ph(U)     deg
                                          1.4576E-10 E Hdot      W
 sameas  0  Gas type                      1.4576E-10 F Work      W
 mylar      Solid type                      -0.2596  G HeatIn    W
!--------------------------------- 8 ---------------------------------
 HARDEND    8
     0.0000  a R(1/Z)          = 8G?      1.9332E+04 A |p|       Pa
     0.0000  b I(1/Z)          = 8H?      -179.99    B Ph(p)     deg
                                          4.0619E-14 C |U|     m^3/s
                                          -111.78    D Ph(U)     deg
                                          1.4576E-10 E Hdot      W
                                          1.4576E-10 F Work      W
                                          4.0673E-13 G R(1/Z)
 sameas  0  Gas type                      1.0173E-12 H I(1/Z)
 ideal      Solid type                     288.19    I   T       K

! The restart information below was generated by a previous run
! You may wish to delete this information before starting a run
! where you will (interactively) specify a different iteration
! mode.  Edit this table only if you really know your model!
INVARS       4  0  2  0  3  0  6  3  5
TARGS        4  3  6  5  6  8  1  8  2
SPECIALS     0
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